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Implementation of Zirconium Diboride Burnable Absorber Coatings in CE Nuclear Power Fuel Assembly Designs

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April 2003

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Abstract

The Westinghouse Electric Company, LLC (Westinghouse) will introduce the zirconium diboride Integral Fuel Burnable Absorber (ZrB_2 IFBA) design into the CE Nuclear Power (CE) 14x14 and 16x16 fuel assembly designs. The ZrB_2 is coated onto the outer surface of the uranium dioxide (UO_2) fuel pellet stack prior to loading into the fuel rod cladding tubes rather than being mixed with the UO_2 as is done with other IFBA materials (e.g., erbia or gadolinia). As the B-10 absorber burns out, the fuel rod is left with no residual absorber worth as is the case with other IFBA materials like erbium or gadolinium. However, the burnout of the B-10 absorber results in production of helium gas which is released into the fuel rod plenum, [

] [a,c] The helium production effect on internal gas pressure and gas conductivity is taken into account in the design and safety evaluations in CE designed PWRs using the Nuclear Regulatory Commission (NRC) approved models and properties currently used in the Westinghouse designed PWRs. Neutronics codes already contain the capability to predict behavior of the ZrB_2 IFBA absorber. Consequently, only the simple addition of a ZrB_2 IFBA helium generation and release model in the FATES3B fuel performance code is required. Although FATES3B predicted fuel rod internal conditions (pressures, temperatures, etc.) are ZrB_2 IFBA specific for input to other analyses, no coding modifications are required for other design and safety analysis codes. It is the purpose of this topical report to describe the implementation and effect of using the ZrB_2 IFBA coating on the CE fuel assembly design and safety analyses.

Acronyms

BOL	Beginning-of-Life
CE	CE Nuclear Power
CEA	Control Element Assembly
DNBR	Departure from Nucleate Boiling Ratio
ECCS	Emergency Core Cooling System
EM	Evaluation Model
IFBA	Integral Fuel Burnable Absorber
LBLOCA	Large Break Loss-of-Coolant Accident
LHR	Linear Heat Rate
LOCA	Loss-of-Coolant Accident
MTC	Moderator Temperature Coefficient
NCLO	No-Clad-Lift-Off
NRC	Nuclear Regulatory Commission
PCI	Pellet-Clad-Interaction
PCT	Peak Clad Temperature
PWR	Pressurized Water Reactors
SBLOCA	Small Break Loss-of-Coolant Accident
SER	Safety Evaluation Report
SIT	Safety Injection Tank
STP	Standard Temperature and Pressure
WABA	Wet Annular Burnable Absorber
Westinghouse	Westinghouse Electric Company, LLC
UO_2	Uranium Dioxide
ZrB_2	Zirconium Diboride

1.0 INTRODUCTION

1.1 PURPOSE AND SCOPE

Westinghouse Electric Company LLC (Westinghouse) customers operating CE designed pressurized water reactors (PWRs) have indicated a desire to implement zirconium diboride (ZrB_2) integral fuel burnable absorber (IFBA) fuel designs. Therefore, the ZrB_2 IFBA design is being introduced into the fleet of CE 14x14 and 16x16 fuel assembly designs. It is the purpose of this report to describe the implementation and influence of ZrB_2 IFBA on the CE fuel assembly design and safety analyses. Fuel performance, fuel mechanical design, Emergency Core Cooling System (ECCS) performance analyses for Loss-of-Coolant Accidents (LOCAs), non-LOCA transient analyses, and neutronics are described.

1.2 BACKGROUND

The Westinghouse Electric Company, LLC (Westinghouse) has had considerable fabrication and operational experience with the ZrB_2 Integral Fuel Burnable Absorber (IFBA). The ZrB_2 IFBA fuel has operated successfully for more than fifteen (15) years in a broad range of Westinghouse PWRs. ZrB_2 is applied as a very thin uniform coating on the outer surface of the UO_2 fuel pellet stack prior to loading into the fuel rod cladding tubes. As the B-10 absorber burns out, the fuel rod is left with no residual absorber worth as is the case with other absorber materials (e.g., erbia or gadolinia). However, the burnout of the B-10 absorber results in production of helium gas which is released into the fuel rod gas plenum. The neutronics effect, the helium production effect on internal gas pressure, and mechanical effect of the coating thickness are all taken into account in the design and safety evaluations for CE designed PWRs as described herein.

The ZrB_2 IFBA coatings may be natural or enriched with the B-10 isotope to increase the neutronic effectiveness. The enriched B-10 isotope is currently used in all Westinghouse IFBA designs. To obtain the proper peaking factor control, the ZrB_2 coating thickness is varied (i.e., 1.0X, 1.5X, 2.0X loadings, etc.). The ZrB_2 IFBA coating is applied over the center of the UO_2 pellet stack length and does not extend to either end of the fuel rod. The ends without ZrB_2 IFBA are referred to as cutback regions. The fuel pellets in the cutback regions may be solid, annular, or a combination of solid and annular geometry (i.e., solid pellet at the bottom of the pellet stack with annular pellets at the top of the pellet stack) and may be at reduced U-235 enrichment (blankets). However, the ZrB_2 IFBA coating is applied only to central solid fuel pellet stack. $ZrBr_2$ IFBA fuel rods are loaded into an assembly in specific core design locations as a matrix of ZrB_2 IFBA and UO_2 fuel rods. ZrB_2 IFBA fuel rods are introduced into the CE design, safety, and licensing analyses in a manner similar to that approved for Westinghouse designed PWR fuel assemblies (References 92, 94, and 95). Introduction of the IFBA design into CE designed PWRs requires a relatively small perturbation in CE design and licensing codes and methodology.

The B-10 isotope absorbs a neutron and fissions into helium and lithium. Helium is released from the thin coating into the fuel rod plenum by the time complete burnout is attained. This added helium contributes to the rod internal pressure at end of life. [

] [a,c] This is typically referred to as the IFBA loading and is denoted as 1.0X, 1.5X, 2.0X, etc.

It is the purpose of this report to describe the implementation and effect of ZrB_2 IFBA on the CE fuel assembly design and safety analyses. Fuel performance, fuel mechanical design, ECCS analyses, non-LOCA accident analyses, and neutronics are described.

1.3 WESTINGHOUSE ZRB_2 IFBA EXPERIENCE

ZrB_2 IFBA fuel rods have been used successfully in Westinghouse designed PWRs for more than fifteen (15) years since the first region was loaded in 1987. Several hundred regions of ZrB_2 IFBA fuel have been used in more than forty (40) plants. In addition, Westinghouse had introduced the ZrB_2 IFBA fuel design in Fort Calhoun, a CE designed PWR, and ZrB_2 IFBA fuel was used in Fort Calhoun for several reloads. No fuel failures are associated with ZrB_2 IFBA coatings in Westinghouse or CE designed PWRs.

Current Westinghouse ZrB_2 IFBA fuel rod production is on the order of [ ] [a,c] rods per year. ZrB_2 IFBA fuel rods are used extensively in 14x14, 15x15, 16x16, and 17x17 Westinghouse PWR core designs, providing significant and sufficient experience to justify the introduction of the ZrB_2 IFBA fuel into the CE designed PWRs on a full batch basis. Westinghouse fuel rod designs, where ZrB_2 IFBA coatings have been used, range from [
] [a,c] Post-irradiation examinations of ZrB_2 IFBA test rods revealed no profilometry anomalies in the coated fuel pellet zone, no chemical interaction between the coating and fuel rod cladding, no incipient cracks in the cladding inner diameter, no excessive fuel pellet cracking, nor any anomalies in the fuel structure. The ZrB_2 coating effectively remains in place throughout the irradiation.

1.4 SUMMARY

Helium gas generation and release models for the ZrB_2 IFBA coating have been incorporated into the FATES3B fuel performance code. Existing neutronics codes already contain the necessary models for ZrB_2 IFBA. The effect of ZrB_2 IFBA on mechanical design and safety analyses was evaluated. It is concluded that the influence of ZrB_2 IFBA is relatively minor and no significant design or licensing issues exist because of the introduction of the ZrB_2 IFBA design into CE designed PWRs.

Figure 1-1 Typical Fuel Rod Design
14x14 ZrB_2 IFBA

a, c

Figure 1-2 Typical Fuel Rod Design
16x16 ZrB_2 IFBA

a, c

2.0 ZRB_2 IFBA PROPERTIES IN DESIGN AND LICENSING

No new isotopic materials are being added to the ZrB_2 IFBA fuel rod. Neutronic properties of ZrB_2 are standard properties already existing in the Westinghouse neutronics codes for both Westinghouse and CE designed PWRs. Verification of the application of CE neutronics codes for the ZrB_2 design is provided in Section 3.1.

The addition of the ZrB_2 IFBA coating does, however, provide a helium source as the B-10 burns out. The helium is effectively accounted for in the FATES3B fuel performance code in much the same way as standard xenon and krypton fission products are tracked and taken into account.

In addition, the ZrB_2 coating effectively reduces the fuel-clad gap and affects pellet-clad mechanical interaction. The reduction in the as-fabricated gap and its effect on design and licensing are described below.

2.1 BORON DEPLETION CORRELATION

The fractional B-10 depletion from the ZrB_2 IFBA coating has been found to correlate well to fuel burnup and U-235 enrichment. Westinghouse developed a depletion correlation based on detailed physics analyses. The FATES3B depletion equation is identical to that used in the Westinghouse PAD fuel performance code, Reference 95, and is given by

[ ]a, c (1)

where [ ]a, c

This equation covers

- enrichments from 0.74 to 5.0 w/o,
- burnups from beginning-of-life to end-of-life, and
- is applicable to a broad range of assembly lattice types

The above conditions bound CE fuel designs.

[ ]a,c

2.2 HELIUM RELEASE

Absorption of a neutron by the B-10 isotope in the ZrB_2 (depletion) results in the production of one helium atom (He-4) and one lithium atom (Li-7). Thus, considering the mass balance from the nuclear reaction, the depletion of a lb-mole of B-10 results in a lb-mole of helium gas, and the balance remains as solid lithium. The gaseous helium escapes from the ZrB_2 IFBA coating and will contribute to the gas composition mix within the fuel-clad gap and other internal void volumes. Consequently, the helium contributes to fuel-clad gap conductance and fuel rod internal gas pressure. This helium is taken into account in the FATES3B fuel performance code in a manner similar to the standard gaseous fission products released from irradiated UO_2 fuel.

The mass of the released helium is given by

[ ] a, c (2)

where

[ ] a, c

and the total mass of helium released, M_{Helium}^{Total}, is obtained by a summation over the axial fuel rod nodes, N, which are coated with ZrB_2. The helium gas volume at STP is then computed from

$$V = M_{Helium}^{Total} * \bar{v} \tag{3}$$

where $\bar{v}$ is the specific volume from the Perfect Gas Law used in FATES3B

$$\bar{v} = \frac{RT}{P} = 6.205*10^5 \frac{inches^3}{lb-mole} \tag{4}$$

where

$$R = 1545 \frac{ft-lbs_f}{(lb-mole)^{\circ}R}$$

$$T = 492^{\circ}R$$

$$P = 14.7\,psia$$

Definition of the helium release fraction R_f [

]^{a,c}

[

]^{a,c}

2.3 ZRB$_2$ IFBA DESIGN AND LICENSING MODELS AND PROPERTIES

The required design and licensing models for ZrB_2 IFBA are simple and relatively straightforward. Implementation of ZrB_2 IFBA for helium release and the thermal and mechanical effects of the coating are described below. The CE implementation is similar to the implementation of the NRC-approved Westinghouse models.

2.3.1 Fuel Performance

The ZrB_2 depletion and the helium generation and release models described in Sections 2.1 and 2.2 are incorporated into the FATES3B fuel performance code. [

]^{a,c} As previously described, the released helium is added to the gap gas composition and the helium partial pressure is added to the fuel rod internal gas pressure.

In addition, the thickness of the ZrB_2 IBFA coating [

]^{a,c}

[

]^{a,c}

2.3.2 Safety Analysis Initial Conditions

The safety analyses (ECCS and non-LOCA) initial conditions, [

]^{a,c} are based on the FATES3B data and predicted initial conditions prior to the assumed accident. Consequently, there are no changes required to the ECCS and non-LOCA codes and models due to the ZrB_2 IFBA.

2.3.3 Fuel Mechanical Design

Section 2.3.1 describes the incorporation of a new model in the FATES3B fuel performance code to account for the helium release associated with the burnout of the B-10. The resulting fuel rod internal pressures calculated by FATES3B are used as input to the mechanical design evaluations for stress, strain, fatigue, and collapse. Section 2.3.1 also describes the treatment of the ZrB_2 coating [

]^{a,c} Since fuel rod internal pressure and initial fuel pellet diameter are handled the same as previously handled, no model changes are required in the mechanical design evaluations as a direct result of the ZrB_2 coating.

2.4 ANNULAR FUEL PELLET CONSIDERATIONS

The application of ZrB_2 IFBA may require the use of annular fuel pellets to provide additional void volume inside the fuel rod. Additional volume may be needed in order to meet maximum internal pressure limits, e.g., no-clad-lift-off. FATES3B incorporates annular fuel pellet capability as documented in the NRC approved fuel performance topical report, Reference 3. Although radial power and temperature distributions in annular fuel pellets provide thermal margin (i.e., lower temperatures) relative to solid fuel pellets at identical linear heat generation rates (LHGRs), the annular fuel pellets will be implemented only at the low power ends of the fuel rods (typically the top and bottom 5%, approximately). Therefore, the use of annular fuel pellets will not affect core operating margin. An evaluation of annular fuel pellets on ECCS evaluations and non-LOCA evaluations is discussed in Section 4. No annular fuel pellet models are required other than that in the FATES3B fuel performance code to determine internal hot gas pressures.

3.0 BENCHMARKING AND VERIFICATION

The benchmarking and verification of ZrB_2 IFBA is primarily through comparisons between computer code results to demonstrate that performance predictions will be similar within Westinghouse and CE designed PWRs.

3.1 NEUTRONICS

The presence of ZrB_2 as a thin coating on UO_2 fuel pellets in PWR fuel poses no additional requirements on the methods used for core neutronics design. Westinghouse currently has two neutronics design methodologies, each capable of accurately modeling the neutronics behavior of the ZrB_2 IFBA fuel. These are DIT-ROCS and PHOENIX-ANC, which are described in References 49, 53, 89, 90, 91, and 92. In addition, a third neutronics methodology, PARAGON-ANC (Reference 93), may be used to model core configurations containing ZrB_2 IFBA when PARAGON is approved by the NRC.

The neutron cross-sections of boron-10 are well known, and have been used in DIT and PHOENIX-P to compute the reactions of B-10 in soluble boron, in discrete burnable absorbers (Al_2O_3-B_4C and Wet Annular Burnable Absorbers, or WABAs), and in control rods. B-10 is relatively easy to calculate, unlike gadolinium and to a lesser degree erbium, and there are no unique requirements on spatial, spectral and depletion aspects of the calculation methods. The calculation of the neutronics of ZrB_2 IFBA is easier than that of the self-shielded burnable absorbers. A comparison of the references listed above shows that with respect to modeling features relevant to ZrB_2 IFBA, DIT is similar to PHOENIX-P, and that ROCS is similar to ANC.

PHOENIX-P and ANC are already licensed as the primary neutronic modeling tools for all Westinghouse reloads, most of which contain ZrB_2 IFBA. They have also been used for the reload analysis of CE designed PWRs (e.g., Fort Calhoun and Millstone 2), both with and without ZrB_2 IFBA. In addition, several benchmark comparisons between DIT-ROCS, PHOENIX-ANC on plants containing erbia, gadolinia, and ZrB_2 burnable absorbers has produced results that are essentially the same.

3.2 FUEL PERFORMANCE

The ZrB_2 IFBA depletion model is based on Westinghouse neutronics calculations as described in Section 2.1. Depletion and helium release incorporated in the FATES3B fuel performance code have been verified by a comparison to the Westinghouse PAD (Reference 95) results for the same fuel rod design and irradiation history. It can be seen, Figure 3-1, that the results are essentially identical.

Figure 3-1

a, c

4.0 DESIGN AND LICENSING EFFECT OF ZRB_2 IFBA

4.1 EFFECT ON APPROVED TOPICAL REPORTS

The sections which follow provide a Roadmap discussion of the effect of ZrB_2 IFBA on CE design and safety analyses in the areas of fuel performance, fuel mechanical design, ECCS performance safety analysis for LOCA, non-LOCA transient analysis, and nuclear design. The implementation of the ZrB_2 IFBA is independent of cladding material and UO_2 models and properties, but NRC approval of the CE designed PWRs is currently, and will continue to be, limited to a peak pin average burnup of 60 MWd/kgU.

4.1.1 Fuel Performance

The current fuel performance models and methodology topical reports begin with Reference 38 as the base topical report. Additions and modifications to Reference 38 have been provided as supplements to augment the initial description. References 2 and 3 provided upgrades to the fuel performance code to reflect new performance data and extending models to higher burnups.

The currently approved fuel performance code FATES3B, References 2, 3, and 38, is supplemented by the ZrB_2 IFBA fuel helium generation and release models described in Section 2.0. This topical report, therefore, supplements References 2, 3, and 38.

The maximum internal pressure criterion report, Reference 11, previously supplemented the FATES3B topical reports. Reference 11 also provides fuel performance models for potential DNB propagation due to the higher internal gas pressures. However, no changes are required to the maximum pressure criterion, nor is there any direct impact of ZrB_2 IFBA on the fuel and cladding models in this approved topical, Reference 11. Reference 11 was supplemented with the ZIRLO™ cladding models of Reference 55. References 11 and 55 are unchanged because of the implementation of ZrB_2 IFBA or the need for annular pellets.

The gadolinia and erbia burnable absorbers are described in approved topical reports References 49 and 50 for gadolinia and Reference 53 for erbia. These topical reports also supplemented the FATES3B topical reports on the treatment of gadolinia and erbia in FATES3B. References 49, 50, and 53 are unchanged by the implementation of ZrB_2 IFBA fuel. The ZrB_2 IFBA treatment described herein supplements the FATES3B topical reports in a manner similar to the gadolinia and erbia burnable absorber topical reports as stated above.

In summary, the fuel performance topical reports are unchanged by the implementation of ZrB2 IFBA except as supplemented herein.

4.1.2 Fuel Mechanical Design

An assessment of the introduction and effect of ZrB_2 IFBA fuel on CE designed PWRs has determined that there is no effect on the fuel mechanical design. A review of applicable fuel mechanical design and licensing basis documents (References 12, 13, 42, 43, 47, 48, 54, and 55) was performed to determine the effect on fuel mechanical performance due to the implementation of the ZrB_2 IFBA fuel pellets. The survey has determined that there are no model changes required within fuel mechanical design in order to meet design criteria. [

]^{a,c}

4.1.3 ECCS Performance Evaluations

The versions of the Westinghouse ECCS Performance EMs for CE designed PWRs, with ZrB_2 IFBA fuel, are the 1999 Evaluation Model (1999 EM) for Large Break LOCA (LBLOCA) and the Supplement 2 Evaluation Model (S2M) for Small Break LOCA (SBLOCA). Table 4.1.3-1 lists the topical report references and the NRC's Safety Evaluation Reports (SERs) associated with the 1999 EM and the S2M.

The 1999 EM includes the following computer codes: CEFLASH-4A and COMPERC-II perform the blowdown and refill/reflood hydraulic analyses, respectively. In addition, COMPERC-II calculates the minimum containment pressure and FLECHT-based reflood heat transfer coefficients. STRIKIN-II performs the hot rod heatup analysis. COMZIRC, which is a derivative of the COMPERC-II code, calculates the core-wide cladding oxidation percentage. Refer to Table 4.1.3-1 for the references and SERs for these computer codes.

The S2M uses the following computer codes: CEFLASH-4AS performs the hydraulic analysis prior to the time that the Safety Injection Tanks (SITs) begin to inject. After injection from the SITs begins, COMPERC-II is used to perform the hydraulic analysis. COMPERC-II is used in the SBLOCA EM for larger break sizes which exhibit prolonged periods of SIT flow and significant core voiding. The hot rod heatup analysis is performed by STRIKIN-II during the initial period of forced convection heat transfer and by PARCH during the subsequent period of pool boiling heat transfer. Refer to Table 4.1.3-1 for the references and SERs for these computer codes.

The 1999 EM and S2M are NRC-accepted for ECCS performance analyses of CE designed PWRs fueled with either Zircaloy-4 or ZIRLO™ clad fuel assemblies.

A review of the documentation basis of the 1999 EM and the S2M listed in Table 4.1.3-1, which included a review of the respective SERs, identified and dispositioned the following potential issues with respect to applying the EMs to CE designed PWRs containing ZrB_2 IFBA fuel:

1. As required by the SER for the LBLOCA EM (Reference 72), the volumetric average fuel temperature at the maximum power location in the LOCA calculation (CEFLASH-4A and STRIKIN-II) must be equal to or greater than that calculated by the approved version of the FATES3B fuel performance code. Since the fuel pellet material properties in FATES3B do not require modification in order to analyze ZrB2 IFBA fuel, no changes to the ECCS EMs are required. The changes to FATES3B for the helium gas release and fuel rod internal pressure, and the addition of the ZrB2 coating thickness, are directly linked as input to the LBLOCA codes. Therefore, this SER constraint on the interface between the LBLOCA codes and the FATES3B fuel performance code continues to be met.
2. In the S2M, the hot rod heatup calculation is initialized at the burnup with the highest initial fuel stored energy. This approach may not yield a limiting peak cladding temperature for ZrB_2 IFBA fuel because of variations in the timing of cladding rupture due to the [ ]^{a,c} in

the rod internal pressure of a ZrB_2 IFBA fuel rod at burnups near the burnup with the highest initial fuel stored energy. As described in Section 4.2.3.2, a parametric study of rod internal pressure is included in SBLOCA analyses to ensure that the potentially adverse influence of the timing of cladding rupture on peak cladding temperature (PCT) is captured in the analysis.

3. The fuel rod models in the 1999 EM and S2M computer codes assume the fuel pellet is solid and the fuel pellet stack is axially uniform. This precludes the ability to explicitly model annular fuel pellets in only the upper and lower extremities of the fuel pellet stack, if they are employed. The studies described in Section 4.2.3 demonstrate that explicit modeling of annular fuel pellets at the upper and lower extremities of the pellet stack [ ] a, c
4. The fuel pellet models in the EM computer codes [ ] a, c for the effects of the ZrB_2 coating on the fuel pellet properties (e.g., specific heat, thermal conductivity, emissivity, etc.). [ ] a, c
5. The SER supporting the application of the 1999 EM and S2M to fuel designs with ZIRLO™ cladding (Reference 88) states that future changes to LOCA methodologies and/or constituent models require documentation supporting the change(s) that includes justification of the continued applicability of the methodology or model to ZIRLO™. There is no impact on the applicability of the methodology to analyze ZrB_2 IFBA fuel with ZIRLO™ cladding material.
6. The SER supporting the LBLOCA cladding rupture model in the 1999 EM (Reference 62) requires that the cladding rupture temperature be no higher than 950 °C (1742 °F) for fuel designs with Zircaloy-4 cladding. This SER constraint will continue to be met. This SER constraint does not apply to fuel rod designs with ZIRLO™ cladding.

4.1.4 Non-LOCA Transient Safety Analysis

The NRC-approved topical reports for non-LOCA transient safety analysis, References 28, 44, 45, 52, 57, 60, 71, and 75 were reviewed for this evaluation.

As discussed in Section 4.2.4 below, an evaluation was performed to determine if any of the changes associated with ZrB_2 IFBA would require a revision to current codes and methods used for the analysis of non-LOCA transient events. The review considered the effect of ZrB_2 IFBA implementation on core neutronics characteristics and on fuel mechanical design. It was determined that the current methodology remains valid for ZrB_2 IFBA fuel in CE designed PWRs.

4.1.5 Nuclear Design

The NRC-approved topical reports which address neutronics capability for the nuclear design of CE designed PWRs are Reference 89 for ROCS/DIT, References 90, 91, and 92 for PHOENIX and ANC. PARAGON, another neutronics methodology (Reference 93), is currently under NRC review. All have existing capability to treat the neutronic effects of ZrB_2 IFBA fuel. Application of gadolinia and erbia burnable absorbers in CE designed PWRs is provided by References 49, 50, and 53, which are also NRC-approved. Consequently, there are no neutronics models or methodology changes required to implement ZrB_2 IFBA fuel rod designs for CE designed PWRs.

Table 4.1.3-1

Topical Reports and Safety Evaluation Reports for the 1999 EM and the S2M

Subject	Topical Report Reference	SER Reference
LBLOCA Evaluation Model (CENPD-132)	14	72
Supplement 1	15	72
Supplement 2	16	74
Supplement 3	17	62
Supplement 4	18	82
SBLOCA Safety Evaluation Model (CENPD-137)	32	72
Supplement 1	33	70
Supplement 2	34	83
CEFLASH-4A (CENPD-133)	19	72
Supplement 2	21	72
Supplement 4	23	82
Supplement 5	24	62
CEFLASH-4AS		
Supplement 1 to CENPD-133	20	72
Supplement 3 to CENPD-133	22	70
COMPERC-II (CENPD-134)	25	72
Supplement 1	26	72
Supplement 2	27	62
STRIKIN-II (CENPD-135)	28	72
Supplement 2	29	72
Supplement 4	30	65
Supplement 5	31	80
PARCH (CENPD-138)	35	72
Supplement 1	36	72
Supplement 2	37	66
HCROSS		
Appendix A to Enclosure 1 to LD-81-095	56	62
COMZIRC		
Appendix C to CENPD-134 Supplement 1	26	72
Application of FLECHT Correlation to 16x16 Fuel Assemblies (CENPD-213)	46	67
Application of NUREG-0630 Cladding Rupture and Swelling Models (Enclosure 1 to LD-81-095)	56	62
Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs (CENPD-404-P-A)	55	88

4.2 ANALYSIS PROCEDURES AND METHODOLOGY

The sections which follow describe the typical effect of ZrB_2 IFBA fuel rod design on the design and safety analyses performance of CE designed PWRs.

4.2.1 Fuel Performance

4.2.1.1 Analysis

The analysis of ZrB_2 IFBA fuel and the comparisons to urania-erbia and UO_2 fuel presented in this section are intended to demonstrate the relative effect of the properties on various fuel performance parameters. Plant-specific evaluations were performed for reload analyses of cores which include the ZrB_2 IFBA fuel. The approach taken was to utilize typical CE fuel rod designs and to assume fuel rod power histories that typically bound anticipated operation. The power histories generally simulate operation to the core linear heat generation rate (LHGR) limits and, when applicable, to certain fuel rod design limits. For example, [

]^{a,c}

Analysis of ZrB_2 IFBA fuel, urania-erbia fuel, and UO_2 fuel in a standard reload analysis for a specific core may result in a predicted maximum internal hot gas pressure that is [ ]^{a,c} the design pressure limit.

4.2.1.2 Fuel Design

Current generation fuel rod designs typical of CE designed 14x14 and 16x16 fuel assembly fuel are evaluated and results presented. The characteristics of each fuel type analyzed are summarized in Table 4.2-1. ZrB_2 IFBA characteristics for the 14x14 and 16x16 fuel assembly designs summarized in Table 4.2-1 are representative of designs expected to be implemented [

]^{a,c} The ZrB_2 IFBA fuel rod design for a specific reload application may differ from the demonstration designs of Table 4.2-1. Table 4.2-1 shows ZrB_2 IFBA fuel rod design parameters for eight representative designs. These designs include two ZrB_2 coated fuel rods for each of the 14x14 and 16x16 fuel assembly designs, i.e., one ZrB_2 IFBA fuel rod with all solid fuel pellets, and a second ZrB_2 IFBA fuel rod with annular fuel pellets in a short segment on each end of the fuel pellet stack (see the schematic in Figure 1-1). The designs also include a third urania-erbia fuel rod and a fourth UO_2 fuel rod each for the 14x14 and 16x16 fuel assembly designs.

4.2.1.3 Assumed Power Histories

Bounding power histories, based on the most limiting and highest expected B-10 loading design (the ZrB_2 IFBA with all solid pellets in these demonstration analyses were most limiting because of the high B-10 loading), were used in the evaluations for these typical 14x14 and 16x16 fuel assembly fuel rods. These power histories include use of [

]^{a,c}. Note, however, that cycle specific power histories are also used in the design and licensing if they bound the specific cycle. The bounding radial peaking factors for the 14x14 and 16x16 designs are shown in Figures 4.2-1 and 4.2.2.

The evaluations of the relative thermal performance of the 14x14 fuel rod designs consisted of comparing the ZrB_2 IFBA fuel rods with the urania-erbia and the UO_2 fuel rod thermal performances using identical input power histories. Similarly, the evaluations to compare relative thermal performance of the 16x16 fuel rod designs consisted of comparing the ZrB_2 IFBA fuel rods with the urania-erbia and the UO_2 fuel rod thermal performances using identical input power histories. The power history used for the 14x14 fuel rods is different than, but similar to, the power history used for the 16x16 fuel rods.

4.2.1.4 Results

<u>14x14 Design</u>

The fuel rod maximum internal hot gas pressures for the 14x14 ZrB_2 IFBA fuel rods, the urania-erbia fuel rod, and the UO_2 fuel rod [ ]^{a,c} are shown in Figure 4.2-3. [

]^{a,c}

<u>16x16 Design</u>

The fuel rod maximum internal hot gas pressures for the 16x16 ZrB_2 IFBA fuel rods, the urania-erbia fuel rod, and the UO_2 fuel rod [ ]^{a,c} are shown in Figure 4.2-4. [

]^{a,c}

4.2.1.5 B-10 Coating

The effect of the ZrB_2 coating is to increase the hot gas pressures due to the release of helium gas from the coating as the burnable absorber boron in the ZrB_2 coating is depleted. The representative ZrB_2 IFBA fuel rods evaluated herein had an enriched boron [

]^{a,c}

4.2.1.6 Conclusions

It is concluded that the fuel performance of the ZrB_2 IFBA fuel rod design will satisfy the same performance criteria as required of the UO_2, erbia, and gadolinia fuel rod designs currently operating in CE designed PWRs.

4.2.2 Fuel Mechanical Design

Section 4.1.2 describes the influence of the ZrB_2 IFBA fuel pellets on the various aspects of the mechanical design of the fuel rods and fuel assemblies. As documented in that section, the mechanical design aspects that require evaluation are those that are a function of the fuel rod internal pressure or the initial fuel pellet diameter. The pertinent mechanical design topics are cladding stresses, cladding strain, cladding fatigue, and cladding collapse. Reference 55 (ZIRLO™ report) contains the most recent discussion of these topics (Sections 5.4.2, 5.4.3, 5.4.4, and 5.4.1, respectively). Evaluations of the effect of the ZrB_2 IFBA fuel pellets on each of these topics have been performed using typical 14x14 and 16x16 fuel rod design configurations. The evaluations are discussed below.

4.2.2.1 Cladding Stress

Cladding stress is affected by fuel rod internal pressure, but it is not affected by the fuel pellet diameter. Due to the NCLO maximum pressure criterion, the maximum fuel rod internal pressures are constrained to be comparable between the ZrB_2 IFBA fuel rods and the non-IFBA fuel rods. Since tensile cladding stresses are associated with maximum fuel rod internal pressures, the tensile cladding stresses of the ZrB_2 IFBA fuel rods and the non-IFBA fuel rods will be comparable. [

]^{a,c} Evaluation of the effect of the [ ]^{a,c} minimum pressure on compressive cladding stresses demonstrated that both the 14x14 and 16x16 fuel rod designs continue to satisfy their cladding compressive stress criteria while accommodating the [ ]^{a,c} fuel rod internal pressures associated with the ZrB_2 IFBA fuel rods.

4.2.2.2 Cladding Strain

Cladding strain is a function of the fuel rod internal pressure, as well as the pellet-to-clad gap. With regard to the use of the ZrB_2 IFBA fuel pellets, only the effect of the increased fuel pellet diameter will be evaluated since high fuel rod internal pressures maximize cladding strain predictions and, as discussed above, the maximum rod internal pressures have not increased. The impact of the reduced pellet-to-clad gap has been evaluated for both the 14x14 and 16x16 fuel rod designs with ZrB_2 IFBA fuel pellets. The evaluations demonstrated that both fuel rod designs continue to satisfy their cladding strain criterion while accommodating the reduced pellet-to-clad gap associated with the ZrB_2 IFBA fuel pellets.

4.2.2.3 Cladding Fatigue

Cladding fatigue is also a function of both rod internal pressure and pellet-to-clad gap. Both [ ]^{a,c} rod internal pressures and reduced pellet-to-clad gaps increase predicted cladding cumulative fatigue damage factors. Therefore, the effects of both these parameters were included in the evaluation of the 14x14 and 16x16 feul rod designs with ZrB_2 IFBA fuel pellets. The evaluations demonstrated that both fuel rod designs continue to satisfy their cladding fatigue criterion while accommodating the [ ]^{a,c} fuel rod internal pressures and the reduced pellet-to-clad gap associated with the ZrB_2 IFBA fuel designs.

4.2.2.4 Cladding Collapse

The reduced pellet-to-clad gap of the ZrB_2 IFBA pellets does not affect cladding collapse predictions, but [ ]^{a,c} initial rod internal pressures do. Evaluations of the cladding collapse times in the active fuel region of the rods were made with the [ ]^{a,c} rod internal pressures using the CEPAN computer code for both the 14x14 and 16x16 rod design. The evaluation demonstrated that the predicted collapse times for both designs were in excess of their required residence time. [ ]^{a,c} Thus, cladding collapse is not a concern for the ZrB_2 IFBA fuel design.

4.2.2.5 Conclusion

The impact of the incorporation of ZrB_2 IFBA fuel pellets on the mechanical design aspects of the 14x14 and 16x16 fuel rods is presented above. The results of evaluations are included for cladding stresses, cladding strain, cladding fatigue, and cladding collapse. The evaluation of each topic has demonstrated that both the 14x14 and 16x16 fuel rod designs with ZrB_2 IFBA pellets satisfy the applicable design criteria.

4.2.3 ECCS Performance Evaluations

This section describes the application of the Westinghouse Emergency Core Cooling System (ECCS) Performance Evaluation Models (EMs) for CE designed PWRs to the analysis of ZrB_2 IFBA fuel for Large Break and Small Break Loss-of-Coolant Accidents (LBLOCA and SBLOCA).

Section 4.1.3 describes a survey of the ECCS performance analysis EMs that identifies the applicable licensing basis documents, limitations and constraints, and the fuel properties and behavior characteristics important to the implementation of ZrB_2 IFBA fuel for CE designed PWRs for both the LBLOCA and SBLOCA EMs.

Section 4.2.3.1 describes the approach for modeling ZrB_2 IFBA fuel for LBLOCA and Section 4.2.3.2 describes the approach for SBLOCA EMs. Conclusions regarding the implementation of ZrB_2 IFBA fuel in the CE LBLOCA and SBLOCA ECCS performance EMs are presented in Section 4.2.3.3.

The Westinghouse post-LOCA Long Term Cooling EM for CE designed PWRs (Reference 96) does not model a fuel rod to the level of detail that is affected by the implementation of ZrB_2 IFBA fuel. Consequently, the post-LOCA Long Term Cooling EM is unaffected and, therefore, not addressed herein.

As described in Sections 1.0 and 2.0 above, a ZrB_2 IFBA fuel rod contains UO_2 fuel pellets with a thin ZrB_2 coating on the fuel pellet surface. A ZrB_2 IFBA fuel rod consists of ZrB_2 coated fuel pellets over the majority of the fuel pellet stack with uncoated UO_2 fuel pellets at the top and bottom of the fuel pellet stack. Additionally, the UO_2 fuel pellets at the extreme ends of the fuel pellet stack may be of an annular design. The ECCS evaluations described below are based on this ZrB_2 fuel rod design concept.

4.2.3.1 Large Break Loss-of-Coolant Accident

ZrB_2 IFBA fuel is represented in LBLOCA ECCS performance analyses via normal code inputs. Also, the LBLOCA ECCS performance analysis process applies, as approved by the NRC, to ZrB_2 IFBA fuel. The following is a list of LBLOCA input parameters that represent the standard plant specific and design specific aspects pertinent to the introduction of ZrB_2 IFBA fuel:

- Fuel performance parameters such as pellet surface roughness, fission gas composition, initial centerline temperature versus linear heat rate, initial cladding and pellet dimensions, initial fuel rod internal pin pressure and gas volume distribution versus burnup are input through the link to the FATES3B fuel performance code and through other standard fuel specific computer code inputs.
- Similarly, physics parameters such as axial power shape, radial peaking and pin power census are input through standard physics related computer code inputs.

Demonstration analyses for typical ZrB_2 IFBA fuel rod designs for both 14x14 and 16x16 fuel assemblies show no significant change in PCT (typically < 50 °F change, which depends on the ZrB_2 IFBA fill gas pressure) and maximum cladding oxidation compared to non-ZrB_2 IFBA fuel rod designs. Implementation analyses are performed to determine the plant-specific impact of the ZrB_2 IFBA fuel.

The LBLOCA demonstration analyses were performed for both configurations of ZrB_2 IFBA fuel described above, that is, with and without annular fuel pellets at both ends of the fuel rod. The fuel performance characteristics of the designs with and without annular fuel pellets are represented by their FATES3B fuel performance data which are linked to the LBLOCA model. [

]^{a,c}:

1. [

]^{a,c}.

2. [

]^{a,c}.

4.2.3.2 Small Break Loss-of-Coolant Accident

Similar to LBLOCA analyses using the 1999 EM, ZrB_2 IFBA fuel is modeled via computer code inputs in SBLOCA analyses with the S2M. Consequently, no computer code changes are required to analyze ZrB_2 IFBA fuel..

As described in Section 4.2.1 above, because of the gas release associated with ZrB_2 IFBA fuel, the variation of fuel rod internal pressure with burnup is [ ]^{a,c} for a ZrB_2 IFBA fuel rod than it is for a non-ZrB_2 IFBA fuel rod (e.g., a UO_2 or erbia fuel rod), particularly at lower burnups. Also, to compensate for the [ ]^{a,c} gas release, the initial fill gas pressure for a ZrB_2 IFBA fuel rod is [ ]^{a,c} than that of a non-ZrB_2 IFBA fuel rod. For example, a typical fill gas pressure for a non-ZrB_2 IFBA CE fuel rod is approximately [ ]^{a,c} psia. In comparison, the fill gas pressure for a ZrB_2 IFBA CE fuel rod may be approximately [ ]^{a,c}

For a SBLOCA analysis using the S2M, the hot rod heatup calculation is performed at the burnup for which the initial fuel rod stored energy is highest (Reference 32, page 18). Typically, this occurs at a burnup of approximately 500 to 1000 MWD/MTU. For the CE fuel rod design, the initial fuel rod internal pressure [ ]^{a,c} at such low burnups. For example, for a typical 14x14 fuel assembly, the initial fuel rod internal pressure for the hot rod changes by [ ]^{a,c} between 500 and 1000 MWD/MTU and by approximately [ ]^{a,c} between 0 and 8000 MWD/MTU. In contrast, the initial rod internal pressure increases by approximately [ ]^{a,c} between 500 and 1000 MWD/MTU for a ZrB_2 IFBA fuel rod with annular pellets. Likewise, it increases by [ ]^{a,c} between 0 and 8000 MWD/MTU. See Figures 4.2-3 and 4.2-4 for typical fuel performance characteristics.

Because of the [ ]^{a,c} in fuel rod internal pressure for ZrB_2 IFBA fuel at low burnup and [ ]^{a,c}, the hot rod heatup calculation of a ZrB_2 IFBA fuel rod may show [ ]^{a,c} differences in PCT over a [ ]^{a,c} range of burnups.

As a result, a hot rod heatup calculation performed at the burnup with the maximum initial fuel stored energy may not be limiting. For example, a hot rod heatup calculation performed at an earlier burnup with [ ]^{a,c} may result in cladding rupture being delayed until later in the hot rod heatup transient when the cladding temperature is approaching its peak value. If the cladding temperature at this delayed rupture time is above the threshold temperature for cladding oxidation, the rupture may produce a rapid increase in cladding temperature due to the oxidation process.

A parametric study of rod internal pressure is included in SBLOCA analyses to ensure that the potentially adverse impact of the timing of cladding rupture on peak cladding temperature described above is captured in SBLOCA analyses. The limiting break is first identified by means of the break spectrum analysis, which is performed at the burnup corresponding to the maximum initial fuel rod stored energy. The parametric study is then performed to determine if a rod internal pressure different from the pressure at the burnup with the maximum initial fuel stored energy results in an increase in peak cladding temperature for the limiting break. In particular, the pool-boiling hot rod heatup calculation for the limiting break of the break spectrum is reanalyzed over the range of rod internal pressures identified by the hot rod fuel performance analysis. A sufficient number of rod internal pressures is analyzed in the parametric study to ensure that, if cladding rupture is predicted to occur for the limiting break, it occurs at a time that results in the maximum peak cladding temperature. To the extent required for a plant-specific analysis, the parametric study is performed for each fuel design covered by the analysis (e.g., ZrB_2 IFBA fuel rod and UO_2 fuel rod; Zircaloy-4 cladding and ZIRLO™ cladding).

A SBLOCA analysis of a typical ZrB_2 IFBA fuel rod design shows that, excluding the potential impact of the fuel rod internal pressure parametric study, implementation of ZrB_2 IFBA has an insignificant effect (i.e., < 50 °F change) on PCT, whereas including the impact of the parametric study may have a significant effect (i.e. > 50 °F). Implementation analyses are performed to determine the plant-specific impact of ZrB_2 IFBA fuel.

<u>Annular Fuel Pellets</u>

[

]^{a,c}

4.2.3.3 Conclusions

EM surveys for both LBLOCA and SBLOCA have been conducted and the influence of the introduction of ZrB_2 IFBA fuel on the methodology basis has been addressed. Westinghouse concludes that no changes to the 1999 EM or S2M computer codes are required to implement ZrB_2 IFBA fuel, including ZrB_2 IFBA fuel rod designs that contain annular fuel pellets.

For LBLOCA, the gap conductance and internal fuel pin pressure models receive relevant interface data or initial conditions for ZrB_2 IFBA fuel through the link to FATES3B fuel performance code in the same manner as for non-ZrB_2 IFBA fuel. For SBLOCA, these aspects of the fuel pellet model are controlled through computer code inputs in the same manner as for non-ZrB_2 IFBA fuel.

For a ZrB_2 coated fuel pellet, material properties such as thermal conductivity, emissivity, and density are modeled [ ]^{a,c} as described in Sections 2.0 and 2.3.

Evaluation model surveys for both LBLOCA and SBLOCA demonstrate that current SER constraints and limitations continue to apply, as described in Section 4.1.3.

Special studies were conducted for both LBLOCA and SBLOCA that show that annular pellet regions at the top and bottom of the ZrB_2 IFBA fuel rod can be represented [

]^{a,c}

4.2.4 Non-LOCA Transient Safety Analysis

This section addresses the effect of the implementation of ZrB_2 IFBA fuel on the non-LOCA accident analyses. ZrB_2 IFBA related changes were evaluated to determine if any of the changes would require a revision to current codes and methods used for the analysis of non-LOCA events. It was determined that the current methodology remains valid for IFBA cores.

The evaluation included consideration of the following IFBA-related effects:

4.2.4.1 Changes to Core Neutronics Characteristics

Core Peaking

Core axial and radial peaks are an input to the non-LOCA safety analyses. An important effect of ZrB_2 IFBA implementation on the non-LOCA transient safety analyses is through the effect on core power peaking. Section 3.1 discusses the impact of ZrB_2 IFBA implementation on power peaking. The effect is relatively small and any change in core power peaking due to implementation of ZrB_2 IFBA will be accommodated in the same way as normal cycle-to-cycle changes.

Burnup Dependence of MTC

As a result of the more rapid burnout characteristics of ZrB2 IFBA, peak soluble boron concentration may occur sometime after beginning-of-cycle (BOC). As a consequence, peak positive MTC may occur later than BOC. However, non-LOCA transient safety analyses use bounding values of MTC that bound all times in core life. The bounding values remain valid for the ZrB2 IFBA fuel design.

4.2.4.2 Fuel Mechanical Design Characteristics

Decrease in Fuel Gas Gap

The ZrB2 IFBA fuel pellets will have a slightly larger radius than the standard UO2 fuel pellets so that the gas gap at BOC will be smaller. This will have a small effect on the gap heat conductance. Non-LOCA safety analyses use values of the gap conductance that bound all times in core life. The bounding values remain valid for the ZrB2 IFBA fuel design.

Gas Release

As discussed in Section 2.2, helium gas release occurs for the ZrB_2 IFBA fuel design. However, this is not a significant parameter for the non-LOCA transient safety analyses, and does not impact the results of the non-LOCA transient analyses.

Annular Fuel Pellets

The ZrB_2 IFBA fuel rod design may include a region of annular pellets at the top and bottom of the fuel rod. This feature is discussed in Section 2.4 above. The purpose of the annular fuel pellet region is to provide void volume to accommodate gas released by the burnup of B-10.

A review was performed to determine if the annular pellet region could be limiting for any of the design basis non-LOCA transient events. The review determined that the annular region would never be limiting. Consequently, the current methodology, which models the solid pellets, remains valid. This conclusion was based on the following considerations:

- The bounding core properties used as input to the non-LOCA transient analyses remain valid for the ZrB2 IFBA fuel design including annular fuel pellets.
- Thermal hydraulic behavior of the annular fuel region is unchanged. Therefore, the results of events that use DNBR as a criterion are not affected.
- It is expected that the annular fuel pellet design will be less likely than the solid fuel pellet design to induce cladding failure during energy insertion transients.
- The power in the annular fuel region will be well below that of the peak power in the solid fuel for all conditions of normal operation and transients.
- It was determined that only the CEA Ejection event could be potentially be impacted by the annular fuel pellets. However, an evaluation of the CEA ejection accident found that the deposited energy and temperature in the annular pellet region was significantly lower than the values obtained for the solid pellet region due to the lower power peaking in the annular fuel.

4.2.4.3 Conclusions

A review of the non-LOCA licensing basis analyses for CE designed PWRs was performed. It was determined that the current methodology remains valid for the analysis of ZrB_2 IFBA fuel and, furthermore, will provide bounding results for the ZrB_2 IFBA design.

The effect of the ZrB_2 IFBA design on the results of the non-LOCA transient analyses is small and will be accommodated in the same way as normal cycle-to-cycle changes.

4.2.5 Nuclear Design

This section describes the impact of ZrB_2 IFBA on the nuclear aspects of core design.

In general the behavior of a core with ZrB_2 IFBA is similar to that of a core with erbium burnable absorber, except that ZrB_2 IFBA exhibits no special spectral interaction with moderator temperature. Thus, a greater BOC reactivity hold-down and associated lower soluble boron is required with ZrB_2 IFBA to achieve the same MTC as with erbium. Since ZrB_2 IFBA burns out completely, additional ZrB_2 IFBA can be added as necessary to control MTC, without an ore/SWU penalty.

While ZrB_2 IFBA burns out a little faster than does erbium, ZrB_2 IFBA does not exhibit the extremely rapid burnout that is sometimes observed with low concentrations of gadolinium. Power peaking factors are similar between ZrB_2 IFBA and erbium, and usually lower than what can be achieved with gadolinium, for the same number of feed assemblies. The primary macroscopic characteristics of a core using ZrB_2 IFBA are a lower required soluble boron concentration at BOC and a lower average feed enrichment.

While the ZrB_2 IFBA fuel rods could be composed of all solid UO_2 pellets, it is common for ZrB_2 IFBA fuel rods to incorporate a small region of annular pellets at each end of the fuel stack. This design feature helps reduce the peak internal pressure, as described earlier in this report. The axial power for such regions is less than the average axial power, even without the use of axial blankets (typically at lower U-235 enrichment and lower power). With axial blankets the power in the annular region would be, therefore, substantially less than the average axial power.

In addition to the natural tendency for power to be lower near the ends of the core, the reduced mass of UO_2 in an annular fuel pellet results in an additional power offset relative to a nearby solid pellet. That is, for approximately the same incident fine-group neutron spectrum, the annular fuel produces less power. This power reduction is of the order of the volumetric fuel displacement.

Table 4.2-1
Fuel Rod Design Parameters

a, c

Table 4.2-1 (continued)
Fuel Rod Design Parameters

a, c

Figure 4.2-1 Maximum Allowable Radial Peaking Factor 14x14 Fuel Design

a, c

Figure 4.2-2 Maximum Allowable Radial Peaking Factor 16x16 Fuel Design

a, c

Figure 4.2-3 Maximum Internal Gas Pressure
14x14 Fuel Design

a, c

Figure 4.2-4 Maximum Internal Gas Pressure
16x16 Fuel Design

a, c

5.0 Conclusions

The ZrB_2 IFBA fuel rod design consists of a ZrB_2 coating on the outer diameter of UO_2 fuel pellets over the center region of the fuel rod with cutback regions (regions without ZrB_2 coating) on both ends of the fuel rod. Lower enrichment fuel pellets may also be used in a portion of the cutback region. The cutback regions may consist of solid, annular, or a solid and annular fuel pellet combination as described in Section 1.1.

ZrB_2 helium gas generation and release are incorporated into the FATES3B fuel performance code in a manner similar to the approved Westinghouse PAD implementation of ZrB_2 IFBA. Thickness of the ZrB_2 coating is accounted for in the fuel-clad gap and mechanical interaction models where appropriate. Neutronic codes already contain the capability to model ZrB_2 IBFA fuel rods. An engineering evaluation was performed for the impact of ZrB_2 IFBA on fuel rod design and safety analyses in the areas of fuel performance, fuel mechanical design, ECCS performance evaluations, non-LOCA transient safety analyses, and neutronic design. No significant issues were found to exist.

Consequently, the ZrB_2 IFBA fuel rod design can be implemented for CE designed PWRs on a full batch basis without significant design and licensing perturbations.

6.0 REFERENCES

1. CEN-121(B)-P, "Methods of Analyzing Sequential Control Element Assembly Group Withdrawal Event for Analog Protected Systems", November, 1979 SER dated Sept 2, 1981
2. CEN-161(B)-P, Supplement 1-P-A, "Improvement to Fuel Evaluation Model," March 1992
3. CEN-161(B)-P-A, "Improvement to Fuel Evaluation Model," August 1989
4. CEN-183(B)-P, "Application of CENPD-198 to Zircaloy Component Dimensional Changes," September 1981
5. CEN-193(B)-P, "Partial Response to NRC Questions [Nos. 8, 10-13] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," January 29, 1982
6. CEN-193(B)-P, Supplement 1-P, "Partial Response to NRC Questions [Nos. 7 and 9] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," March 4, 1982
7. CEN-193(B)-P, Supplement 2-P, "Partial Response to NRC Questions [Nos. 1 - 6] on CEN-161(B)-P, Improvements to Fuel Evaluation Model," March 21, 1982
8. CEN-205(B)-P, "Response to NRC Questions on FATES-3 and the Calvert Cliffs 1 Cycle 6 Reload," April 23, 1982
9. CEN-220(B)-P, "Supplemental Information on FATES-3 Stored Energy Conservatism," October 5, 1982
10. CEN-345(B)-P, "Response to Questions on FATES3B," October 17, 1986
11. CEN-372-P-A, "Fuel Rod Maximum Allowable Gas Pressure," May 1990
12. CEN-382(B)-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 14x14 PWR Fuel," August 1993
13. CEN-386-P-A, "Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel," August 1992
14. CENPD-132P, "Calculative Methods for the C-E Large Break LOCA Evaluation Model," August 1974
15. CENPD-132P, Supplement 1, "Calculational Methods for the C-E Large Break LOCA Evaluation Model," February 1975
16. CENPD-132-P, Supplement 2-P, "Calculational Methods for the C-E Large Break LOCA Evaluation Model," July 1975
17. CENPD-132, Supplement 3-P-A, "Calculative Methods for the C-E Large Break LOCA Evaluation Model for the Analysis of C-E and W Designed NSSS," June 1985
18. CENPD-132, Supplement 4-P-A, "Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model," March 2001
19. CENPD-133P, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," August 1974
20. CENPD-133P, Supplement 1, "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," August 1974

21. CENPD-133P, Supplement 2, "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis (Modifications)," February 1975

22. CENPD-133, Supplement 3-P "CEFLASH-4AS, A Computer Program for the Reactor Blowdown Analysis of the Small Break Loss of Coolant Accident," January 1977

23. CENPD-133, Supplement 4-P "CEFLASH-4A, A FORTRAN-IV Digital Computer Program for Reactor Blowdown Analysis," April 1977

24. CENPD-133, Supplement 5-A "CEFLASH-4A, A FORTRAN77 Digital Computer Program for Reactor Blowdown Analysis," June 1985

25. CENPD-134P, COMPERC-II, A Program for Emergency Refill-Reflood of the Core", August 1974

26. CENPD-134P, Supplement 1, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core (Modifications)," February 1975

27. CENPD-134, Supplement 2-A, "COMPERC-II, A Program for Emergency Refill-Reflood of the Core," June 1985

28. CENPD-135P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1974

29. CENPD-135P, Supplement 2, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program (Modifications)," February 1975

30. CENPD-135, Supplement 4-P, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," August 1976

31. CENPD-135-P, Supplement 5, "STRIKIN-II, A Cylindrical Geometry Fuel Rod Heat Transfer Program," April 1977

32. CENPD-137P, "Calculative Methods for the C-E Small Break LOCA Evaluation Model," August 1974

33. CENPD-137, Supplement 1-P, "Calculative Methods for the C-E Small Break LOCA Evaluation Model," January 1977

34. CENPD-137, Supplement 2-P-A, "Calculative Methods for the ABB CE Small Break LOCA Evaluation Model," April 1998

35. CENPD-138P, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," August 1974

36. CENPD-138P, Supplement 1, "PARCH, A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," February, 1975

37. CENPD-138, Supplement 2-P, "PARCH A FORTRAN-IV Digital Program to Evaluate Pool Boiling, Axial Rod and Coolant Heatup," January, 1977

38. CENPD-139-P-A (includes Supplement 1-P), "C-E Fuel Evaluation Model Topical Report," April 1975

39. Not Used

40. CENPD-183-(A), "Loss of Flow, C-E Methods for Loss of Flow Analysis", May 12, 1982 (this is the date of the SER inside the cover of the Topical......although the Topical is dated June 1984)

41. CENPD-185-P-A, "Clad Rupture Behavior, LOCA Rupture Behavior of 16x16 Zircaloy Cladding," May 1975

42. CENPD-187-P, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding," April 1976
43. CENPD-187-P, Supplement 1-P-A, "CEPAN Method of Analyzing Creep Collapse of Oval Cladding," June 1977
44. CENPD-188-A, "HERMITE A Multi-Dimensional Space-Time Kinetics Code for PWR Transients," July 1976
45. CENPD-190-A, "CEA Ejection, C-E Method for Control Element Assembly Ejection," July 1976
46. CENPD-213-P, "Reflood Heat Transfer, Application of FLECHT Reflood Heat Transfer Coefficients to C-E's 16x16 Fuel Bundles," January 1976
47. CENPD-225-P-A (includes Supplement s 1, 2 & 3), "Fuel and Poison Rod Bowing," June 1983
48. CENPD-269-P, Rev. 1-P, "Extended Burnup Operation of Combustion Engineering PWR Fuel," July 1984
49. CENPD-275-P, Revision 1-P-A, "C-E Methodology for Core Designs Containing Gadolinia-Urania Burnable Absorbers," May 1988.
50. CENPD-275-P, Revision 1-P, Supplement 1-P-A, "C-E Methodology for PWR Core Designs Containing Gadolinia-Urania Burnable Absorbers," April 1999.
51. CENPD-279, Supplement 6, "Annual Report on ABB CE ECCS Performance Evaluation Models," February 1995
52. CENPD-282-P-A, {Vols. 1 Thru 4 + Supplement 1}, "Technical Manual for the CENTS Code", Vols. 1,2 and 3 - February 1991 and Vol. 4 – December 1992, Supplement 1 – June 1993
53. CENPD-382-P-A, "Methodology for Core Designs Containing Erbium Burnable Absorbers," August 1993
54. CENPD-388-P, "Extension of the 1-Pin Burnup Limit to 65 MWD/kgU for ABB PWR Fuel with OPTIN™ Cladding," February 1998 {currently under NRC review}
55. CENPD-404-P-A," Implementation of ZIRLO™ Cladding Material in CE Nuclear Power Fuel Assembly Designs", November 2001
56. LD-81-095, Enclosure 1-P-A, "C-E ECCS Evaluation Model, Flow Blockage Analysis," December 1981
57. LD-82-001, Enclosure 1-P, "CESEC, Digital Simulation of a Combustion Engineering Nuclear Steam Supply System," January 6, 1982
58. A. C. Thadani (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing C-E Topical Report CEN-372-P, Fuel Rod Maximum Allowable Gas Pressure (TAC No. 69231)", April 10, 1990
59. A. C. Thadani (NRC) to A. E. Scherer (C-E), "Generic Approval of C-E Topical Report CEN-386-P, Verification of the Acceptability of a 1-Pin Burnup Limit of 60 MWD/kgU for Combustion Engineering 16x16 PWR Fuel", (TAC No. M82192), June 22, 1992
60. C. O. Thomas (NRC) to A. E. Scherer (C-E), "Combustion Engineering Thermal-Hydraulic Computer Program CESEC III", April 3, 1984
61. C. Thomas to A. Scherer, "Acceptance for Referencing of Topical Report CENPD-225 (P)", February 15, 1983
62. D. M. Crutchfield (NRC) to A. E. Scherer (C-E), "Safety Evaluation of Combustion Engineering ECCS Large Break Evaluation Model and Acceptance for Referencing of Related Licensing Topical Reports," July 31, 1986

63. E. J. Butcher (NRC) to A. E. Lundvall, Jr. (BG&E) regarding Safety Evaluation Report for "Extended Burnup Operation of Combustion Engineering PWR Fuel" (CENPD-269-P Revision 1-P), October 10, 1985

64. Not Used

65. K. Kniel (NRC) to A. E. Scherer (C-E), "Combustion Engineering Emergency Core Cooling System Evaluation Model," November 12, 1976

66. K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-138, Supplement 2-P," April 10, 1978

67. K. Kniel (NRC) to A. E. Scherer (C-E), August 2, 1976

68. Letter, A. C. Thadani (NRC) to A. E. Scherer (C-E), "Generic Approval of C-E Fuel Performance Code FATES3B (CEN-161(B)-P, Supplement 1-P)", November 6, 1991

69. Letter, A. C. Thadani (NRC) to S. A. Toelle (ABB-CE), "Generic Approval of the Acceptability of 1-Pin Burnup Limit of 60 MwD/Kg for C-E 14x14 PWR Fuel (CEN-382(B)-P) (TAC No. M86305)", June 11, 1993

70. Letter, K. Kniel (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Reports CENPD-133, Supplement 3-P and CENPD-137, Supplement 1-P," September 27, 1977

71. Letter, M. J. Virgilio (NRC) to S. A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CENPD 282-P, Technical Manual for the CENTS Code (TAC No. M82718)", March 17, 1994

    R.C. Jones (NRC) to S.A. Toelle (CE), "Acceptance for Referencing of Licensing Topical Report CENPD-282-P Vol. 4, Technical Manual for the CENTS Code (TAC No. M85911)", February 24, 1995

72. O. D. Parr (NRC) to F. M. Stern (C-E), June 13, 1975

73. O. D. Parr (NRC) to A. E. Scherer (C-E), October 30, 1975

74. O. D. Parr (NRC) to A. E. Scherer (C-E), December 9, 1975

75. O. D. Parr (NRC) to A. E. Scherer (C-E), June 10, 1976

76. O. D. Parr (NRC) to A. E. Scherer (C-E), Untitled, February 10, 1976

77. O. D. Parr (NRC) to F. M. Stern (C-E), "C-E Fuel Evaluation Model Topical Report", December 4, 1974

78. R. A. Clark (NRC) to A. E. Lundvall, Jr. (BG&E), "Safety Evaluation of CEN-161 (FATES 3)," March 31, 1983

79. R. A. Clark (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing of the Topical Report CEN-161, Improvements to Fuel Evaluation Model (FATES3)", May 22, 1989

80. R. L. Baer (NRC) to A. E. Scherer (C-E), "Evaluation of Topical Report CENPD-135 Supplement No. 5," September 6, 1978

81. S. A. McNeil (NRC) to J. A. Tiernan (BG&E), "Safety Evaluation of Topical Report CEN-161(B)-P Supplement 1-P, 'Improvements to Fuel Evaluation Model'", February 4, 1987

82. S. A. Richards (NRC) to P. W. Richardson (Westinghouse CENP), "Safety Evaluation of Topical Report CENPD-132, Supplement 4, Revision 1, 'Calculative Methods for the CE Nuclear Power Large Break LOCA Evaluation Model' (TAC No. MA5660)," December 15, 2000

83. T. H. Essig (NRC) to I. C. Rickard (ABB CENP), "Acceptance for Referencing of the Topical Report CENPD-137(P), Supplement 2, 'Calculative Methods for the C-E Small Break LOCA Evaluation Model' (TAC No. M95687)," December 16, 1997

84. Ashok C. Thadani (NRC) to A. E. Scherer (C-E), "Acceptance for Referencing of Licensing Topical Report CENPD-275-P, Revision 1-P, "C-E Methodology for Core Designs Containing Gadolinia-Urania Burnable Absorbers"," May 14, 1988

85. Cynthia A. Carpenter (NRC) to I. C. Rickard (ABB CENP), "Acceptance for Referencing of Licensing Topical Report CENPD-275-P, Revision 1-P, Supplement 1-P,"C-E Methodology for PWR Core Designs Containing Gadolinia-Urania Burnable Absorbers" (TAC No. M99307)," April 5, 1999

86. Ashok C. Thadani (NRC) to S. A. Toelle (ABB CENP), "Acceptance for Referencing of Topical Report "Methodology for Core Designs Containing Erbium Burnable Absorbers" (TAC Nos. M79067 and M82959)," June 29, 1993

87. David H. Jaffe (NRC) to A. E. Lundvall, Jr. (BGE), Untitled, June 24, 1982

88. S. A. Richards (NRC) to P. W. Richardson (WEC), "Safety Evaluation of Topical Report CENPD-404-P, Revision 0, 'Implementation of ZIRLO Material Cladding in CE Nuclear Power Fuel Assembly Designs' (TAC No. MB1035)", September 12, 2001

89. CENPD-266-P-A, "The ROCS and DIT Computer Codes for Nuclear Design", April, 1983.

90. WCAP-10965-P-A, "ANC, A Westinghouse Advanced Nodal Computer Code," September, 1986.

91. WCAP-11596-P-A, "Qualification of the PHOENIX-P/ANC Nuclear Design System for Pressurized Water Reactor Cores," June, 1998.

92. WCAP-10444-P-A, "Reference Core Report Vantage 5 Fuel Assembly," September, 1985.

93. WCAP-16045-P, Revision 0, "Qualification of the Two-Dimensional Transport Code PARAGON", March 2003.

94. WCAP-10444-P–A, Addendum 1-A, "Reference Core Report Vantage 5 Fuel Assembly", March, 1986

95. WCAP-15063-P-A Revision 1, with Errata, "Westinghouse Improved Performance Analysis and Design Model (PAD 4.0)", July 2000.

96. CENPD-254-P-A, "Post-LOCA Long Term Cooling Evaluation Model", June 1977

WCAP-16072-NP, Rev. 0

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